UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

AD-A239 060

(2)

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
UNLIMITED

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 91 0633

6a. NAME OF PERFORMING ORGANIZATION
CORNELL UNIVERSITY

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
AFOSR

6c. ADDRESS (City, State, and ZIP Code)
ITHACA, NEW YORK 14853

7b. ADDRESS (City, State, and ZIP Code)
BUILDING 410, BOLLING AFB DC 20332-6448

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
AFOSR

8b. OFFICE SYMBOL (If applicable)
NA

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR-89-0346

8c. ADDRESS (City, State, and ZIP Code)
BUILDING 410, BOLLING AFB DC 20332-6448

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2307	A1	

11. TITLE (Include Security Classification)
"VORTEX DYNAMICS"

12. PERSONAL AUTHOR(S)
LEIBOVICH, SIDNEY

13a. TYPE OF REPORT
FINAL TECHNICAL REPORT

13b. TIME COVERED
FROM 6/1/89 TO 5/31/91

14. DATE OF REPORT (Year, Month, Day)
1991, JUNE 27

15. PAGE COUNT
5

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
	20.04	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
AERODYNAMIC VORTICES, VORTEX BREAKDOWN, STABILITY, NONLINEAR TRANSITIONS

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A theoretical description of vortex breakdown incorporating the essential physical processes governing the occurrence, location, and strength of the phenomenon and suitable for design and control purposes, is under development. The strongly decelerated motions, which can have flow reversals and therefore provide a model for vortex breakdown events, found earlier in the course of this project for vortices of aerodynamic type, have been shown to be unstable to three-dimensional perturbations when the deceleration exceeds a threshold value. The nature of the instability agrees with experimental observations and supports a comprehensive theoretical framework for vortex breakdown previously outlined by Leibovich (1984). New numerical algorithms useful for very large stability problems have been developed under grant sponsorship, and have been published or will be shortly submitted for publication. Several other stability and bifurcation problems for rotating pipe flows have been solved. Rotating pipe flows are the simplest known exact viscous flows bearing a qualitative resemblance to vortices with axial streaming, and serve as a convenient theoretical testbed on which to develop an understanding of vortex instability and subsequent nonlinear evolution.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
[illegible]

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22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

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Final Technical Report

Vortex Dynamics

AFOSR-89-0346

Prepared by
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Date submitted: June 26, 1991
Contract Period: June 1, 1989 - May 31, 1991

1 Summary and Significance of Research Accomplished

Vortex breakdown is a three-dimensional, unsteady and intrinsically nonlinear phenomenon. The underlying physical mechanisms are intricately interconnected, and the goal of a comprehensive physical theory is a large and long term one. Experimental evidence makes it clear that the essential features triggering breakdown are the upstream velocity profiles in the vortex core and the external pressure gradients to which the core is subjected. Furthermore, experimental phenomenology makes it reasonably certain that the physical mechanisms involved are propagation of strongly nonlinear waves, amplification of these waves due to forcing effected by the external pressure gradient (not an instability), and secondary three-dimensional instability. All three effects are essential in high Reynolds number flow.

The research program that has been prosecuted addresses these fundamental physical elements in three ways. First, the existence of strongly nonlinear waves in vortices of aerodynamic type was shown in the paper by Leibovich and Kribus (the citations to research here and to follow are to research sponsored by this grant, and listed in section 3 of this report), and the nature of these waves was characterized. The method used to construct these solutions was necessarily numerical, but it was shown that the resulting solutions were of solitary wave form, and were reasonably well approximated by semi-analytical models, even when the waves were highly nonlinear. This latter finding is important if a description of sufficient simplicity to make the control of vortex breakdown a reasonable prospect is to be found. This has been a key objective of our program.

Secondly, the instability of vortical flows of aerodynamic type has been addressed. The motivation for the stability work is threefold. First, one method of controlling vortex breakdown is to alter the characteristics of the vortex, and in particular the velocity profiles. One method of accomplishing this result is to trigger an instability. The paper by Brown et al. uncovered the dominant modes of instability of the leading edge vortex.

A second motivation for studying instability is basic - little is known about the nonlinear consequences of the linear instability of vortices. The thesis of Yang, and the papers by Yang and Leibovich, and by Mahalov and Leibovich, all address this fundamental question. Here nonlinear resonances are found to be possible and to induce stronger growth than "ordinary" linear instabilities. In addition, these resonances lead to intermittency in the flows, and to the irregular birth and death of what might be called coherent structures.

The third motivation is directly related to the role of instability to the mechanics of vortex breakdown. This stability problem of necessity concerns the stability of a (highly) "nonparallel" flow, and very little is known about this kind of problem. Formidable numerical difficulties have hampered progress on such problems, and new numerical methods are required. The thesis and paper by Kribus, and the paper (in progress) by Kribus and Leibovich attack this problem, within the context of the mechanics of vortex breakdown. The strongly nonlinear waves found earlier, and constituting a key feature of vortex breakdown, are found to be unstable to three-dimensional instabilities when the wave amplitude exceeds a threshold that depends on Reynolds number. The form of the dominant eigenfunctions show precisely the kind of asymmetry and spatial distribution seen in experimental realizations of vortex breakdown, a fact that we find very exciting and encouraging. The energy loss to the wave caused by the instability is expected to stabilize the position of the breakdown, and the resulting flow is expected to consist of the (largely intact) remnants of the strongly nonlinear wave together with smaller contributions of the 3D instability.

We believe the instability results, particularly those found by Kribus, will allow us to extract a simple parameterization of the nonlinear effects of the instability, which will be immediately usable in the simple parametric model of vortex breakdown that we believe we now can construct.

The two fundamental questions concerning the role of numerical experiment, and the incorporation of the physical effects of impressed pressure gradients, are raised in two venues by Leibovich. In his plenary lecture to the IUTAM Symposium on Separated Flows and Jets, it was shown how the pressure gradient can be included as an imperfection in the bifurcation problem leading to the nonlinear solitary waves that can propagate on vortex cores. The extreme difficulty of the numerical experiment for flows containing vortex breakdown was also addressed, with particular emphasis on the usual circumstance in which the outflow boundary is placed in a region of the flow that is known from experiment to be simultaneously subcritical (to wave propagation) and unstable. Both of these issues were also discussed in the paper appearing in the volume *Turbulence and Coherent Structures*.

2 Participants

Participants contributing to the research program:

1. Sidney Leibovich, Samuel B. Eckert Professor of Mechanical and Aerospace Engineering, Cornell University

2. Susan N. Brown, Professor of Applied Mathematics, University College, London

3. Abraham Kribus, Graduate Student, Aerospace Engineering, Cornell. PhD, February, 1991. Currently Research Scientist, Department of Environmental Sciences and Energy Research, Weizmann Institute of Science, Rehovot, Israel

   item Zhigang Yang, Graduate Student, Aerospace Engineering, Cornell. PhD, August, 1990. Currently Research Scientist, NASA/ICOMP, Cleveland, OH.

4. Alexis Mahalov, Graduate Student, Center for Applied Mathematics, Cornell.

5. Anping Wang, Graduate Student, Aerospace Engineering, Cornell.

3 Publications

3.1 Papers in refereed journals

All of the papers cited here acknowledge Grant Support. All except one have either already appeared or are now in Press.

- Leibovich, S. and Kribus, A. Large amplitude wavetrains and solitary waves in vortices *J. Fluid Mech.*, **216**, 459-504, July, 1990.
- Brown, S.N., Leibovich, S. and Yang, Z. On the linear instability of the Hall-Stewartson model of the leading edge vortex *Theor. Comp. Fluid Mech.*, **2** , 27-46, 1990.
- Mahalov, A., Titi, E. S. and Leibovich, S. Invariant helical subspaces of the Navier-Stokes equations. *Archives for Rational Mechanics and Analysis.* **112**, 193-222, 1990
- Mahalov, A. and Leibovich, S. Weakly nonlinear analysis of rotating Hagen-Poiseuille flow. To be published in *European J. Mech B. Fluid Mech.*.
- Mahalov, A. and Leibovich, S. Multiple bifurcations of rotating pipe flow *Theor. Comp. Fluid Mech.* (In press.)
- Yang, Z. and Leibovich, S. Nonlinear dynamics near the stability margin in rotating pipe flow, *J. Fluid Mech.* (In press)
- Mahalov, A. and Leibovich, S. On the calculation of coupling coefficients in amplitude equations, Accepted for publication in *J. Comp. Phys.*
- Guckenheimer, J. and Mahalov, A. Resonant triad interactions in systems with O(2) symmetry, Submitted to *Physica D*

3.2 Other publications, including theses

- Leibovich, S. Vortex breakdown: a coherent transition trigger in concentrated vortices. In *Turbulence and Coherent Structures*, ed. by M. Lesieur and O. Métais, Kluwer Acad. Pub., 1990, 285-302.
- Leibovich, S. The local dynamics of vortical flows. Text of Plenary Lecture to *IUTAM Symposium on Separated Flows and Jets*. Novosobirsk, USSR, July 9-13, 1990.
- Kribus, A. Computation of leading eigenspaces for generalized eigenvalue problems. In: Proceedings of the Army Math Conference, West Point, June, 1989.
- Mahalov, A. and Leibovich, S. Amplitude expansions near a degenerate bifurcation point in rotating pipe flow. In: Proceedings of the Army Math Conference, West Point, June, 1989.
- Yang, Z. *Two theoretical studies of stability of swirling flows*. PhD Dissertation, Cornell University, Ithaca, NY, May, 1990.
- Kribus, A. *Large amplitude waves, instabilities, and breakdown in vortex flows*. PhD Dissertation, Cornell University, Ithaca, NY, May, 1991.

3.3 Papers in Progress

All of the following papers exist in draft form, and are expected to be submitted to refereed journals by September, 1991. All acknowledge support from this grant.

- Mahalov, A. and Leibovich, S. Resonant interactions in rotating pipe flow
- Mahalov, A. and Leibovich, S. Triad resonance in Couette-Poiseuille flow
- Yang, Z. and Leibovich, S. On the stability of viscous wall modes in rotating pipe flow
- Kribus, A. and Leibovich, S. Instability of strongly nonlinear solitary waves in concentrated vortex flows.

4 Communications at Scientific Meetings

- S. Leibovich "Static bifurcations of vortices" Brown University, Center for Fluid Mechanics, Turbulence, and Computation, 1989. (Invited)
- S. Leibovich "Vortex breakdown: a coherent transition trigger in concentrated vortices" Invited plenary lecture, in "Turbulence '89: Organized structures and turbulence in fluid mechanics" September 18-21, 1989, University of Grenoble.

- A. Mahalov, A. and S. Leibovich "Weakly nonlinear interactions in rotating Hagen-Poiseuille flow" 42nd Ann. meeting of the Div. of Fluid Dyn.of the Amer. Phys. Soc., Palo Alto, Nov.19-21, 1989.

- S. Leibovich, "Local dynamics of vortical flows" IUTAM Symposium on Separated Flows and Jets, Novosibirsk, July 9-13, 1990. (Invited plenary lecture)

- A. Mahalov and S. Leibovich, "Helical bifurcations and resonant triad interactions in the rotating Hagen-Poiseuille problem" IUTAM Symposium on Nonlinear Hydrodynamic Stability and Transition, Univ. of Nice, September 3-7, 1990. (Invited paper)

- A. Mahalov and S. Leibovich, "Resonant Tollmein-Schlichting Triad Interactions in Channels" 43nd Ann. meeting of the Div. of Fluid Dyn.of the Amer. Phys. Soc., Ithaca, Nov.18-20, 1990. (Bull. APS, 35, 2264, Nov. 1990).

- Z. Yang and S. Leibovich, "Nonlinear evolution of marginally unstable wave packets in rotating pipe flow" . 43nd Ann. meeting of the Div. of Fluid Dyn.of the Amer. Phys. Soc., Ithaca, Nov.18-20, 1990. (Bull. APS, 35, 2235, Nov. 1990).

- S. Leibovich, "Vortex breakdown" School of Engineering, Lehigh University, April 12, 1991.

- Z. Yang and S. Leibovich, "On the stability of viscous wall modes in rotating pipe flow" to be given at the AIAA Fluid and Plasmadynamics Conference, Hawaii, June, 1991.

5 Patents

There were no patents or patent applications.